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Forest migration and carbon sources to Iranian mangrove soils

Hana Etemadi[a,*], Joseph M. Smoak[b], Christian J. Sanders[c]

[a] Environmental Science, Persian Gulf Research Institute, Persian Gulf University, P.O. Box: 7516913817, Bushehr, Iran
[b] Environmental Science, University of South Florida, Florida, 33701, USA
[c] National Marine Science Centre, School of Environment, Science and Engineering, Southern Cross University, Coffs Harbour, New South Wales, Australia

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ABSTRACT

Mangrove forests rank as one of the world's most productive biomes and their soils are highly efficient in accumulating organic carbon (OC). Most research on OC in mangrove forests has focused on moist tropical and sub-tropical regions. Here we examine an arid mangrove forest (composed of the species *Avicennia marina*) from the Jask area in southern Iran. The organic carbon content, TOC:TN ratios and $\delta^{13}C$ signatures indicate that marine algae and microalgae are a greater source of organic material than the terrestrial inputs at three out of the four study sites in this work. Furthermore, sea-level rise as well as geomorphic and topographic differences are contributing to the mangrove landward migration and expansion of 112 ha (or 33%) of these arid forests between 1956 and 2012. This is substantial as up to 0.60 g OC cm^{-2} were found in the upper 42 cm of the soils. However, these values should be taken with caution as the large inorganic carbon deposition in the soils here and in other regions may offset the CO_2 sequestration of the global arid mangroves in terms of climate mitigation.

1. Introduction

Mangroves provide numerous ecological services such as nursery and breeding grounds for fish and invertebrates, coastal protection (e.g., typhoon, flood, and tsunami), and store large amounts carbon (Breithaupt et al., 2012). Coastal ecosystems can have autochthonous and allochthonous sources of organic carbon (OC) input including material from planktonic and terrestrial origin (Bouillon et al., 2003). Studies show that OC storage by mangrove forests is generally two to three times greater than most terrestrial forests (Tue et al., 2012), storing between 547 ± 66 t ha^{-1} in subtropics and temperate regions and 895 ± 90 t ha^{-1} in the tropics (Sanders et al., 2016).

Mangrove forests often contain organic soils up to several meters deep and are ten times more efficient at sequestering carbon dioxide on a per area basis per year than boreal, temperate, or tropical forests (Smoak et al., 2013; Sanders et al., 2014). Therefore preserving and restoring these coastal wetlands have been proposed as a way to sequester CO_2 as a means of mitigating anthropogenic climate change (Schile et al., 2016). However, ongoing natural and human-induced alterations that effects the composition of wetland plant species, the quantity of above ground biomass as well as soil biogeochemistry are not yet fully understood. Uncertainties on estimates of mangrove C storage can be improved by empirical data on soil C, which are currently lacking in many regions around the globe. Increasing the spatial data will help refine estimates of global C storage. The synergy of land use and climate change, including the impacts of sea level rise, presents additional uncertainties in the fate and management of coastal C storage (Donato et al., 2011).

Arid environments cover one third of the Earth's surface, where annual rainfall is less than 250 mm a year and the high evapotranspiration potential as well as intense solar radiation is prevalent (Jafari et al., 2018). Arid mangroves ecosystems are characterized by sever temperatures, sparse and sporadic rainfall, high salinity and low nutrient inputs. They are adapted to survive near the limit of their tolerance at extremes in temperature, rainfall and salinity (Schile et al., 2016). Compared to the moist tropics stands, mangrove forests in the arid-zones have lower biomass and productivity, consist of more dense but smaller trees, and tend to inhabit areas with coarser sediment deposits (Alongi, 2015). While mangrove research has grown steadily in the last 50 years, there are a lack of investigation on mangroves from arid reigns. Mangroves in arid regions, including those located in the south of Iran which are the most northerly distributed in the north hemisphere, may represent very different dynamics as compared to other areas. Studies in these regions are important as they are the least studied marine coastal ecosystems of which the paucity of data concerning carbon research as well as climate change impacts on arid mangroves may create a bias toward moist regions in global investigations on wetland carbon sequestration.

Mangroves in an arid setting in the United Arab Emirate along the arid mangroves in the south coast of the Persian Gulf have lower

* Corresponding author.
E-mail addresses: etemadihana@gmail.com, h.etemadi@pgu.ac.ir (H. Etemadi), smoak@mail.usf.edu (J.M. Smoak), Christian.Sanders@scu.edu.au (C.J. Sanders).

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biomass (Schile et al., 2016) and the organic production and carbon turnover rates are lower than most other regions as they compensate carbon deficit by fast litter decomposition to sustain their metabolism (Sánchez-Andrés et al., 2010). There are only a few reliable reports on the climate change impact and the sources of OC in Iranian mangroves. However, Iran ranks 43rd in the world and 10th in Asia in terms of mangrove area (FAO, 2007). Unlike most mangrove systems that have been examined in wetter climates, these arid forests could be more susceptible to climate change. For instance, Etemadi et al. (2015) reported that the minimum temperatures in the south of Iran increased by +3.14 °C over the past 42 years and predicted a further increase to above 38 °C during warm seasons by 2080–2099. Moreover, indirect effects of a rising temperature are increases in salinity and humidity, which may further exacerbate mangrove survival conditions. Accelerating local SLR in this region and the severe climatic conditions in the south of Iran place these mangrove ecosystem at a climatic threshold.

Increasing sea-level rise (SLR) has been cited as the greatest threat to mangroves, which have responded to past sea-level changes by migrating landward or upward (Krauss et al., 2011). In the 20th century, sea-level has risen approximately 20 cm mainly due to thermal expansion of the oceans and melting of glacial ice caused by global warming. Global average sea levels are projected to rise at a rate of 8 and 16 mm yr^{-1} between 2081 and 2100 (IPCC, 2013). Sea level rise may vary from one location to another due to local factors (e.g. tectonic processes, ocean circulation, elevation changes of the wetland sediment surface, coastal subsidence, and sediment budgets) (McLeod and Slam, 2006). Through landward migration and/or soil-surface elevation changes via accretion of autochthonous and allocthonous material, mangrove ecosystems have been remarkably persistent and resilient during rapid sea-level rise (5–15 mm yr^{-1}) during the late Quaternary Period (Alongi, 2008).

The aim of this study is to: (1) Determine the resilience of the mangrove forests to an accelerating sea level rise (ASLR) and to reconstruct their historical expansion in the south of Iran; (2) Quantify the soil carbon stocks and delineate the origin of organic matter through use of elemental organic C and N ratios as well as their isotopic signals ($\delta^{13}C$ and $\delta^{15}N$); and, (3) Compare inorganic and organic carbon stocks to determine offsets in terms of CO_2 sequestration. Based on the lower primary production in these arid regions with harsh climatic conditions and potentially high inorganic carbon deposition, we hypothesize that these systems are much lower in OC sequestration efficiency than forests in wetter conditions. These differences in OC sequestration efficiencies may intern skew the global average carbon sequestration estimates.

2. Site description

The study area includes three protected areas within Hormaozgan province (East Jask, West Jask and Gabrik Mangrove forests), located between 25°33′ to 25°42′ N latitude and 57°46′ to 58° 35' E longitude. Yekboni estuary (YEK) is located in the West Jask protected area. Shahreno estuary (SH) and Khalasi estuary (KH) are in the East Jask protected area and Gabrik estuary (GET) is situated in Gabrik mangrove forest (Fig. 1). Jask is characterized by arid region with a dry climate condition consisting of hot and dry summers with mild and rainy winters resulting in an excess of evaporation over precipitation. Mean annual rainfall and temperature is 135.56 mm and 26.83 °C respectively (Etemadi , 2014). Water salinity ranges from 36.5 to 41.8 ppt. The grain size of sediment in the study area is 49.15% silt, 32.41% clay, 18.44% sand and 7.84% organic (Azizpour et al., 2014). Tides in Jask coastline are semi-diurnal with approximately 1–4 m tidal range (See Etemadi et al., 2018, for details).

The mangrove forests in this region are dominated by species *Avicennia marina*. *Avicennia* are known to be tolerate to salinity variations and can persist in hypersaline environments. However, the adaptation to the threshold environment in the Persian Gulf might inhibit water uptake and reduce growth. The mangrove forests in the study region are not directly influenced by anthropogenic activities.

3. Methods

3.1. Sediment processing

A sediment core was collected at each study site (Fig. 2) by inserting a 5 cm diameter acrylic tube into the substrate during low tide. The sediment was extruded from the tube and sectioned at 1 cm intervals from the core top down to 30 cm, and at 2 cm intervals from 30 cm depth until the bottom of the core (50 cm). Dry bulk density was determined as the dry sediment weight over the initial wet volume (g cm^{-3}). Two subsamples from each depth interval were dried and ground to powder for carbon analysis. One subsample was acidified to remove carbonates to determine organic carbon and the other subsample was not acidified to determine total carbon. These analyses were performed using a Flash Elemental Analyser coupled to a Delta V IRMS (isotope ratio mass spectrometer), Thermo Fisher. Inorganic carbon was calculated by deducting the organic carbon content from the total organic carbon. The average relative standard deviation based on duplicate samples from the two cores was 0.28% for the OC and TC and 0.02% for N. For analytical precision of stable isotopes, the instrumentation error was less than 0.2‰ for $\delta^{13}C$ and 0.3‰ for $\delta^{15}N$ based on long-term standard deviations of samples compared to standard.

3.2. Remote sensing analysis

Normalized Difference Vegetation Index (NDVI) was applied to three Landsat satellites images from four different years (1972, 1987, 2000, and 2009) to determine land cover changes over four decades. In the secondary analysis stage, a Maximum Likelihood Classification (MLC) program was used to define the mangrove and non-mangrove areas from the extracted vegetation areas using ENVI model (version 4.8). The training areas for mangroves and other vegetation types were selected from the digital aerial imagery due to the high-resolution, and the mangrove boundary was also delineated on this imagery for reference. The displayed image with the above classes was spectrally enhanced by histogram equalization.

Medium scale (1:25,000) black and white panchromatic aerial photographs procured by the www.ngo-iran.ir%2Fngo.htm&ei=Xq7uUMGEBMzJsgbe4oHgBQ&usg=AFQjCNEKsgfQbd01j8YtaJcEifjPTcWSQg&sig2=PjTSVar9y9PyjXOdL3ApQA&bvm=bv.1357700187,d.Yms" > National Geographical Organization of Iran in 1956 were scanned and imported into ArcGIS (ESRI Inc. version 9.2). These were imported as digital images at a resolution 1000 dots per inch. We used tonality (contrast), crown texture, structure, tree height, and relative position on the ground attributes to distinguish mangroves (Kairo, 2001). Field data collected for this study included Ground Control Points (GCPs) for image geo-rectification and spectral signature. The geo-referenced images had RMSE of less than 0.5 pixel which was considered satisfactory. Visual inspection showed that the overlaid images matched each other well.

3.3. Tide gauge data analyses

A trend in the rate of relative sea-level change for Jask Mangrove forest was calculated using mean monthly relative sea-levels obtained from analysis of data from the Jask (25.63ºN, 57.77ºE) and Chabahr (25.2958ºN, 60.630ºE) tide gauge stations. Data sources obtain from Coastal Area Hydrogarphy Management in National Cartographic Center (http://www.ncc.org.ir). Linear and second order polynomial regression models were fit to the mean monthly relative sea-level data at Jask station from January 1997 to February 2011 and in Chabahar station from January 1991 through February 2009, an elapsed period of 19 years.

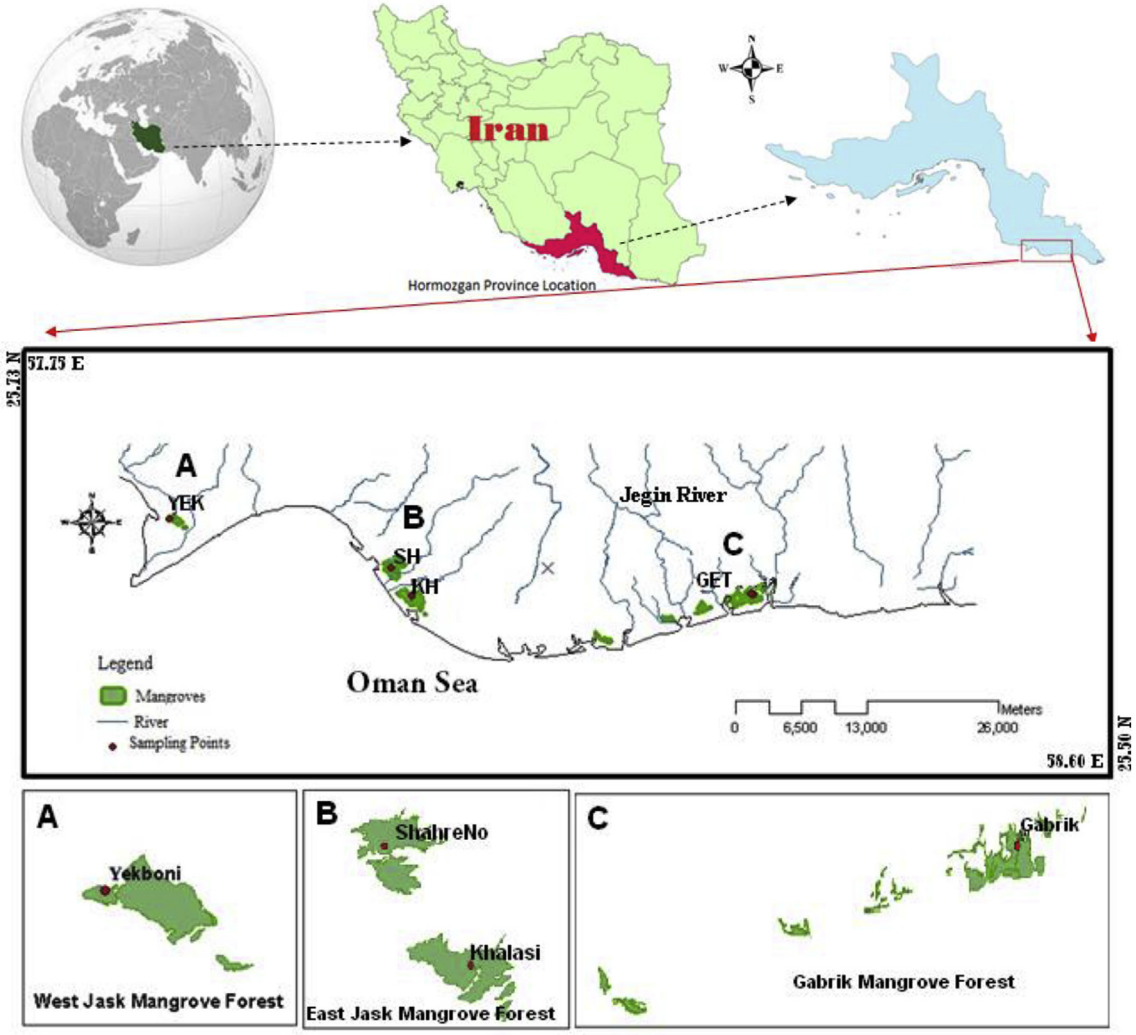

Fig. 1. Location of Core Sediment Samples in Jask mangrove forest.

4. Result

4.1. Organic carbon source

The highest mean value of $\delta^{13}C$, $\delta^{15}N$, TC were observed at the YEK site. The highest mean value of organic carbon content (% OC), total nitrogen, TOC:TN and the lowest value of $\delta^{13}C$ was found at KH site. The mean value of $\delta^{13}C$ for all intervals was −23.58‰. Maximum Standard deviation of sediment profile was measured in inorganic carbon which shows strong variation. In addition, the $\delta^{13}C$ value showed small variation (Table 1). Overall, the % OC of mangrove sediments was found to vary from 0.1 to 1.8%. The mean % OC was 0.5%, and $\delta^{13}C$ value range varied from −19 to −26.9‰. Molar TOC:TN ratios varied between 3.7 and 25.6. Based on the sum of OC in each interval to 42 cm depth, we calculated 0.34, 0.14, 0.60, 0.19 g cm^{-2} OC in YEK, SH, KH and GET mangroves respectively. These OC calculations are based on the single sediment core taken from each area.

Data on carbon stable isotopic composition ($\delta^{13}C$) vs. TOC:TN showed the higher of TOC:TN ratio coincided with more negative $\delta^{13}C$ values in all mangrove sites. There was no statistically significant correlation between TOC:TN ratio and ($\delta^{13}C$) values in KH and SH estuaries (Fig. 2). Also, the higher nitrogen stable isotopic values indicate that the less negative $\delta^{13}C$ represent planktonic and benthic microalgal organic matter source (Meyers, 1994) (Fig. 2, ($\delta^{15}N$) (‰) vs. ($\delta^{13}C$) (‰)). There was no significant change in $\delta^{13}C$ ‰ values associated the increasing % OC at any of the study sites. The same range of $\delta^{13}C$ ‰ had a different value of % OC (Fig. 2, ($\delta^{15}N$) (‰) vs. organic carbon (% OC)). There was a slight positive correlation in GET and YEK estuaries between TOC:TN ratios and $\delta^{15}N$ (Fig. 2, ($\delta^{15}N$) (‰) vs. TOC:TN).

Based on these results, the main source of organic matter in the four study areas from marine POC and algae (Fig. 3, ($\delta^{13}C$) vs. TOC:TN). Most organic source indicators, including TC %, TOC %, TN, $\delta^{13}C$ values, there was little fluctuation with depth and location. However, the TOC:TN ratios and inorganic carbon contents varied between 3.7 to 25.6 and 2.5 to 68.6 (mg cm^{-3}) respectively. The TC % fluctuated showing a gradual decrease with depth. The carbon content is greatest at the YEK site, which had the most inorganic carbon content among the locations studied. The higher TOC and TN contents coincided with lower $\delta^{13}C$ values in all cores (Fig. 4). Furthermore, the highest total organic carbon (TOC %) and total nitrogen (TN) content was found at the KH site, which increased and decreased gradually with depth respectively (Fig. 4). Fluctuation of TN, $\delta^{13}C$ and organic carbon values show a similar pattern. The TOC:TN ratios ranged from 3.7 to 25.6 and showed a general increase with depth except at the GET site (Fig. 4).

4.2. Time series analysis of mangrove area changes

Changes in area from 1956 to 1987 at the Gabrik and West Jask mangrove forests indicated a sharp decrease of around 300 (45.5%) ha and 5 ha (8%) respectively (P-value = 0.002 < 0.01) (Fig. 6). An

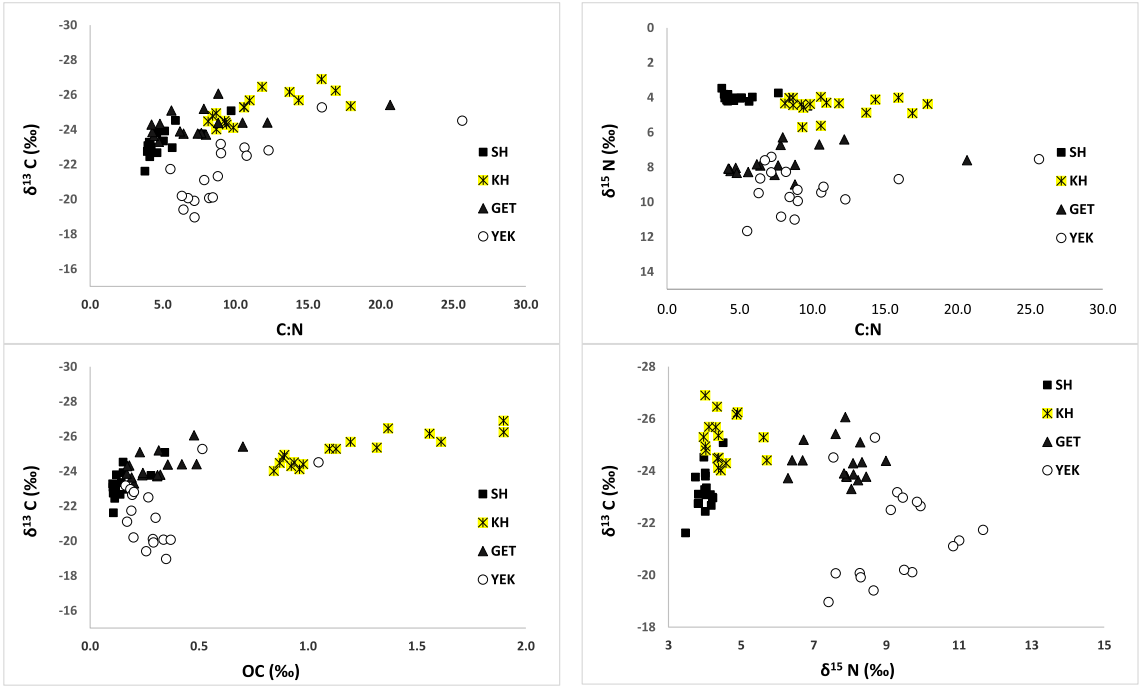

Fig. 2. The scatter plots of δ^{13}C-C/N ratio, δ^{15}N-C/N ratio, δ^{13}C-OC% and δ^{13}C-δ^{15}N in KH, SH, GET and YEK Jask mangrove sample locations.

increase in mangrove area was detected after 1987 in all three areas. This increase was around 6 ha (11%) in West Jask mangroves, 112 ha (33%) in East Jask Mangroves and around 28ha (11%) in Gabrik mangrove forests, respectively. This result demonstrates that the mangrove areas have significantly increased after 1987 while declining just prior to 1998 (P-value = 0.033 < 0.05). Based on this result, a landward migration is observed in the East Jask and Gabrik mangrove forest (Fig. 6). However, in the West, the mangrove forests do not show a landward migration, but rather a reduction in area. Table 2 showed the mangrove area changes from 1956 to 2012.

4.3. Sea level rise

Mean monthly relative sea-level data was calculated by averaging hourly sea-level within each month, which adequately removes sub-annual cyclical tidal constituents. The mean monthly relative sea-level data from January 1990 through December 2009 was taken from the Chabahar tide gauge station, and the data from January 1997 through December 2011 was taken from the Jask tide gauge station. A linear regression model fit to mean monthly sea-levels indicates a mean relative sea-level rise trend of 2.88 mm yr^{-1} over the observed 19 years in Chabahar and sea-level rise trend of 5.47 mm yr^{-1} over the observed 14 years in Jask (Fig. 5). Regional factors account for the differences. Extrapolation suggests sea level will rise by 24 and 47 cm levels in Chabahar and Jask station by the end of the century, respectively.

5. Discussion

Sea-level rise and OC budgets are of concern due to the lack of information needed to compile global OC budgets of mangrove habitats (Bouillon et al., 2008). Very few studies have been conducted on the OC sources and their role in C accumulation and storage in mangroves which are located in arid reigns and their response to sea level change associated with global warming is poorly understood. The Jask forests are similar to other arid mangrove systems, containing relatively small soil carbon pools (Schile et al., 2016). Furthermore, the OC burial in these mangroves may be offset by the relatively large inorganic carbon content in these systems (Saderne et al., 2018). However, the distinct land ward migration observed in the two sites of this work is in contrast with most arid mangroves which have been reported to have been lost in the past several decades (Alongi, 2015).

Data shows the lowest rate of mangrove expansion occurred in Gabrik region (GET site). The main source of freshwater to this region is via the Jegin River, which is a seasonal river. One possible explanation is the decrease in freshwater input as the Kerman catchment area, which was under drought condition in the 1970s. In fact, decreased precipitations at the GET site resulted in notable reduction of mangrove area caused by the conversion of upper tidal zones to drier, hypersaline flats. The Horqin sandy land in Jask are generally thought to be the main sources of sand-dust storms that occur frequently in the arid regions of the northern Oman Sea. The sand movement and irregular grazing by camels were the main reasons for the Jask mangrove degradation in the past (Danekar, 1996). Due to lack of reliable data, an

Table 1
Mean and Standard Deviation (SD) of sediment profile characteristics of four study mangrove sites.

Core	Bulk Density (g cm^{-3})		TC (%)		OC (%)		N (%)		OC (mg cm^{-3})		IC (mg cm^{-3})		TN (mg cm^{-3})		C:N		δ^{13}C (‰)		δ^{15}N (‰)	
Site	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
YEK	1.8	0.3	3.2	0.3	0.3	0.2	0.0	0.0	6.2	5.5	139.2	28.2	0.7	0.3	9.7	4.8	−21.5	1.8	9.5	2.3
SH	1.9	0.3	2.2	0.2	0.1	0.0	0.0	0.0	2.8	1.2	108.2	43.5	0.6	0.1	4.9	1.5	−23.2	0.8	4.0	0.2
KH	1.1	0.2	2.5	0.3	1.1	0.3	0.1	0.0	12.6	2.4	26.9	5.4	1.3	0.2	11.4	3.1	−25.2	0.8	4.4	0.5
GET	1.6	0.2	2.2	0.3	0.3	0.1	0.0	0.0	5.2	2.9	86.9	15.7	0.7	0.1	7.7	4.0	−24.3	0.7	7.7	0.7
Mean	1.6	0.3	2.5	0.3	0.4	0.1	0.0	0.0	6.7	3.0	90.2	23.2	0.8	0.2	8.4	3.3	−23.5	1.0	6.4	0.9

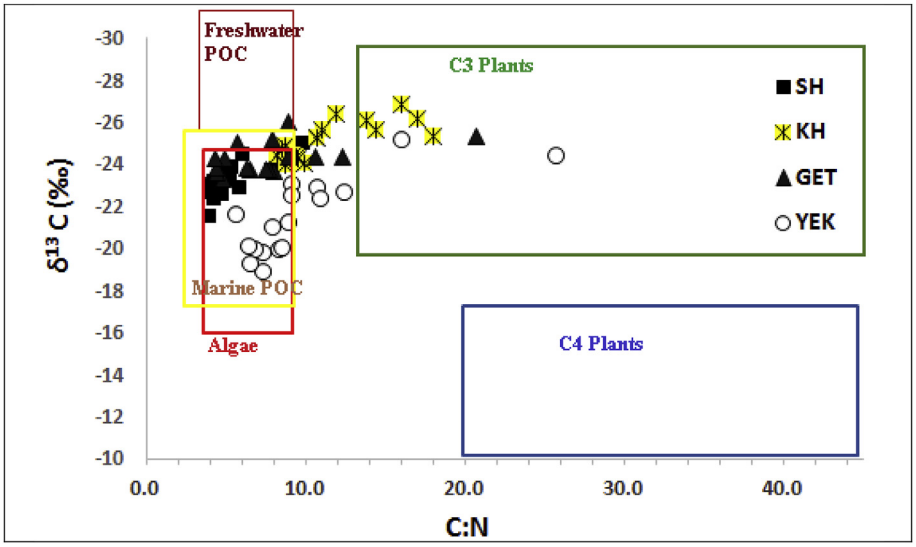

Fig. 3. The scatter plots of δ^{13}C-C/N ratio in Jask mangrove sample locations and Representative δ13C and C/N ranges for organic matter inputs to coastal ecosystems (Lamb et al., 2006).

explanation for the decline of more than 300 ha between 1956 and 1987 cannot be determined.

Mangroves have significantly increased since 1987 in three protected areas. Red Sea mangroves, which are located in the dry and hot climate similar to our study area, showed a slight increase of 15 km^2 or 12% over the 41 years from 1972 to 2013 (Almahasheer and Duarte, 2015). Most of this expansion occurred along the African shore because this area is more suitable for mangrove growth. However, the Tarut Bay in the Persian Gulf Coast of Saudi Arabia has experienced greater than 55% of aerial mangroves loss from 1972 to 2011 due to urban development (Almahsheer et al., 2013). Mangrove forests along arid coasts (e.g., NW Australia, Pakistan, Arabian Peninsula, and both Mexico coasts) are predicted to decline in area as a result of increases in salinities, temperature and a decrease in fresh water availability (Alongi, 2015).

Table 2
Change in mangrove area (ha) from 1956 to 2012.

Study areas	1956	1987	2012
YEK	54.9	50.4	56.5
SH	78.3	101.8	174.4
KH	150.8	154.8	182.1
GET	525.3	208.6	236.6

Relative sea level rise is the predominant factor influencing mangrove position (Krauss et al., 2011). The Laboratory for Satellite Altimetry in NOAA estimated 3.3 ± 0.4 mm yr^{-1} sea level rise in Persian Gulf based on measurements from satellite radar altimeters from 1992 to 2016 (https://www.star.nesdis.noaa.gov). SLR has been estimated to

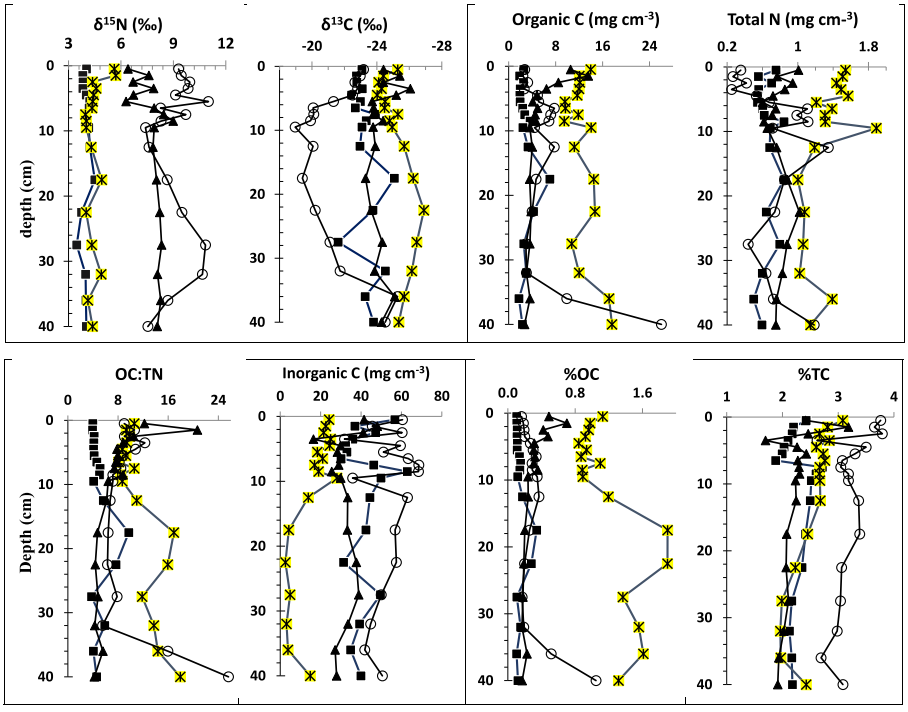

Fig. 4. Depth profiles of soil characteristics for dated intervals of the four soil cores from above to below SH, KH, GET and YEK Mangroves respectively.

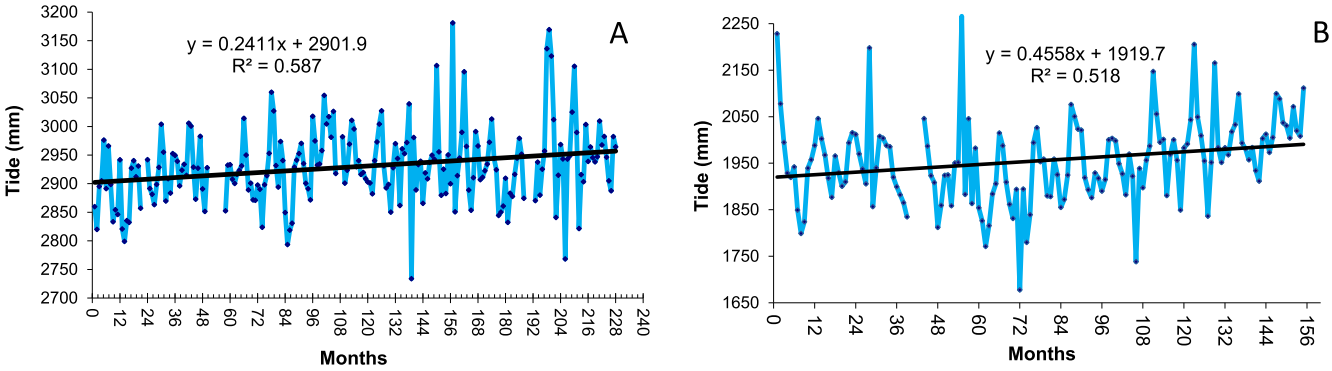

Fig. 5. Relative sea level rise in Chabahar Tide Gauge Station (A) = 2.88 (mm yr^{-1}), in Jask Tide Gauge Station (B) = 5.4 (mm yr^{-1}).

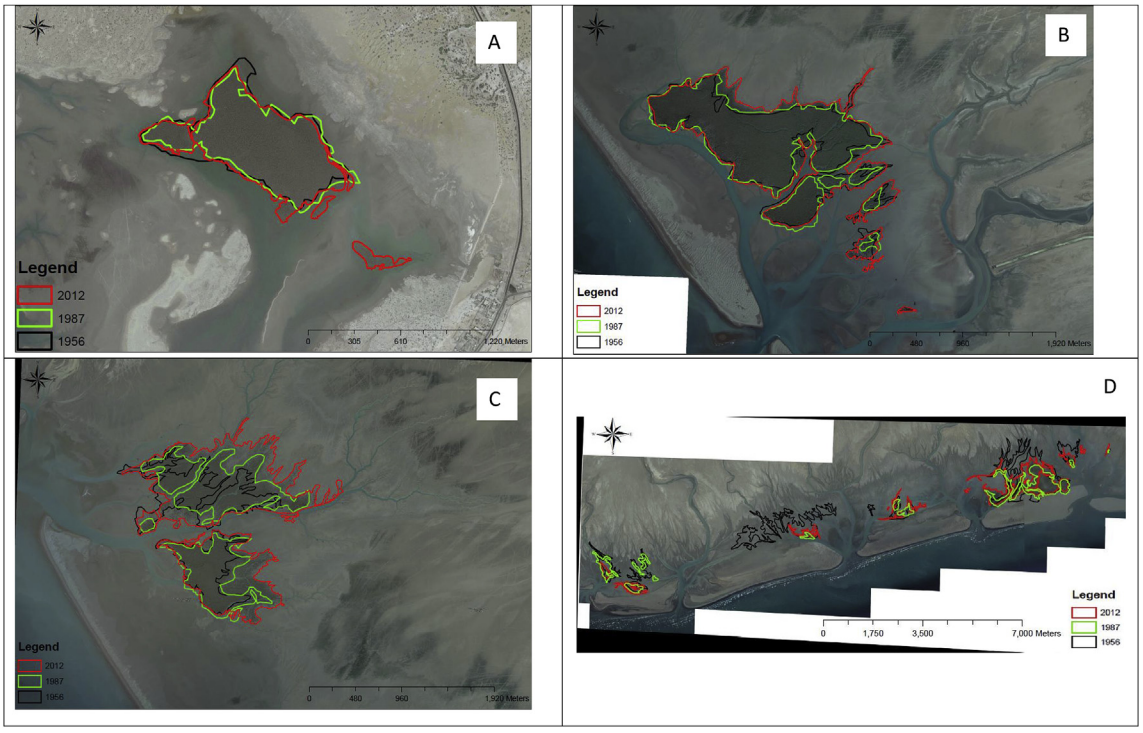

Fig. 6. Change of area during 1956–2012 in A) West Jask, B) East Jask (Khalasi Estuary), C) East Jask (Shahrno Estuary), D) Gabrik Mangrove Forest.

be 3.3 and 2.2 mm yr^{-1} for the period 1979–2007 in the Red Sea and Persian Gulf, respectively with the subsidence rate of 0.7 mm yr^{-1} in Persian Gulf (Alothman et al., 2014; Woodworth et al., 2009). MSLR in this area was 2.8 mm yr^{-1}, which is close to the global sea level rise of 3.2 mmyr^{-1} between 1993 and 2010. Global rates in worst-case scenario are projected to be between 8 and 16 mm yr^{-1} equivalent to a 1.9 m sea level increase over the next 100 years (IPCC, 2013). The reason for the higher sea level rise in Jask station maybe due to the shorter data period (14 years), compared to Chabahar station. Regional sea-level changes have also been influenced by tectonic and isostatic adjustments (i.e., ocean basin deformation, ocean circulation, sedimentation influence, land subsidence and subduction) as well as ocean circulation.

In the past few decades, various investigations on mangroves observed landward migration due to sea-level rise. For instance, mangroves in Ten Thousand Islands region in Florida (Krauss et al., 2011), Louisiana (Perry and Mendelssohn, 2009), Terinad (Ramcharan, 2004), Hawaii (Chimner et al., 2006) all documented landward migration. However, in arid regions where freshwater becomes scarce with increasing salinity and temperature mangrove expansion is uncertain (Alongi, 2015). Similar landward expansion occurred in arid and semiarid region on the Pacific coast of Mexico (Lopez-Medellin et al , 2011) Magdalena Bay, Baja California (Hak et al., 2008). Arid mangroves in Mexico experienced significant losses (3% per year) from 1980 to 2000 in response to the enormous expansion of shrimp farming. This pattern is also evident in arid coasts of northwestern Australia, Pakistan, and the Arabian Peninsula (Alongi, 2015). Studies in these areas concluded that mangrove landward expansion in arid and non-arid zone would be related to local tidal range, physiographic and topographic setting, geological or manmade obstacles, suitable salinity in landward and the portion of coastal development. In our study areas, mangroves are also migrating in a landward direction. Explicit migration was observed in the SH estuary (Fig. 6). These results indicate that the sediment accretion rate is less than the relative sea level rise in Jask Mangrove and therefore the mangroves are not keeping pace with the relative sea level rise. . The delta slope Jask estuaries is less than 0.01–0.1% and the tidal range reaches more than 4m during spring tide in some place in this region, resulting in marine water movement landward greater than 5 km. Sea-level rise is causing an increase in tidal inundation frequency and tidal range, resulting in a decrease in mangrove seedling success rate and a decrease in the rate of photosynthesis. By migrating landward, mangrove seedling have a greater chance to

establish, mature and reproduce (Able et al., 2011).

The average OC soil content found in this study is generally low (mean = 0.4%, Table 1) compared to the global mean OC content of 2.2% (Kristensen et al., 2008). However, a similarly low mean was found in the Qeshm mangrove forest (0.8%) in Iran (Ray and Shahraki, 2016) and along the Red Sea where Almahasheer and Duarte. (2015) found 3 out of 4 of their sites ranged between 0.2 and 0.4% OC. Schile et al. (2016) also reported low soil carbon stocks in an arid mangrove habitat located at the southeast of Persian Gulf due to weakly reducing soil conditions, which reflects the coarse soil texture, high hydraulic conductivity, and low moisture holding capacity as well as the short time period which carbon has been accumulating. These mangroves contained 2.2% soil organic carbon which is greater than what was found in our study region and similar to global mean (Schile et al., 2016). Mangrove in Sundarbans also have low soil carbon content (0.75%) as a result of intense mineralization of organic matter in these intertidal mangrove sediments (Ray et al., 2015). Based on the mangrove areas (ha) in 2013 and OC content, we calculated 1.91, 2.52, 11.03, 4.43 Gg OC in YEK, SH, KH and GET, respectively. In contrast, the desert mangroves located on the coasts of the Baja California accumulate very large amounts of carbon (0.9–3 Gg C/ha) in their sediments. They can keep pace with sea level rise by accreting autochthonous root material (Ezcurra et al., 2016).

While anoxic mangroves soils are well preserved, calcifying epiphytes, macro-algae, and benthic invertebrates, which live in vegetated coastal areas, promote the deposition of detrital $CaCO_3$ particles (Gacia et al., 2002). Water-air CO_2 flux measurements from mangroves surface water suggests that mineralization of organic matter and following CO_2 emission from the water column could also depict a significant CO_2 source and play an important role in the of the oceanic carbon budget (Borges et al., 2005). The acquired ratio of released CO_2 to precipitated $CaCO_3$ is 0.6 in these systems which means for each 1 mol of carbonate precipitated there is a net release of 0.6 mol of CO_2 (Frankignoulle et al., 1995). This ratio will increase as the overall buffer capacity of seawater decreases in response to anthropogenic CO_2 uptake.

From the OC offset calculations in the four sampling sites of this work, inorganic carbon precipitation is significant enough to offset some of the CO_2 removal via OC accumulation, as the results here indicate high calcification rates within the Jask mangrove ecosystem. The highest estimated amount of OC carbon offset was observed in YEK site which may be due to higher abundance of calcifying organism. For instance, Solaimani-Rad (2011) studied macro-benthos community structure in Jask mangroves and demonstrated that the YEK mangroves had the maximum macro-benthos density compared to the KH, SH and GET sites. Both marine calcification-$CaCO_3$ and carbonate dissolution processes occur by releasing CO_2 in surrounding water directly affect CO_2 partial pressure (pCO_2) in the water column and thus CO_2 exchange with the atmosphere. Therefore, as inorganic carbon deposition increases, the OC offset also increases (Howard et al., 2017). An increase in calcification would thus release CO_2 into atmosphere and acts as a positive feedback to human-induced rising atmospheric CO_2 concentrations. Furthermore, McConnaughey et al. (1994) revealed that calcification provides a significant amount of the dissolved CO_2 required for photosynthesis in some ecosystems like coral-algal reef and lakes. Inorganic carbon storage must be considered in seagrass carbon sequestration because CO_2 released by carbonate sediment may also offset seagrass blue carbon storage (Howard et al., 2017). Organic carbon offset through decomposition and the subsequent emission to the atmosphere as greenhouse gases has also been noted by studies in eutrophic mangrove sediments (Sanders et al., 2014; Chen et al., 2016). Results in this study and other research on mangroves in arid zones indicate that these systems play a minor role as CO_2 sinks due to low carbon content, high OC mineralization, and inorganic carbon burial offsets (Almahasheer et al., 2013; Sea et al., 2018, Saderne et al., 2018).

Terrestrial OC is characterized by more negative $\delta^{13}C$ values compared to marine sources, such as plankton, most macro algae, benthic algae, and corals (Sanders et al., 2014). Particulate OC storage within mangrove sediments at a global scale is variable as shown by the wide range of OC content measured in sediments varying between < 2 and < 40 wt.%, with a median particulate OC of 2.20 wt.% (Kristensen et al., 2008). The range of $\delta^{15}N$ value is from −1.5‰ to 3.2‰ in mangrove plant, whereas anthropogenic sources and terrestrial plants contain > 8‰ and ~0‰ respectively (Prasad and Ramanathan, 2009), which may be used in distinguishing nitrogen sources in mangrove ecosystems. The $\delta^{15}N$‰ changed only slightly around 0.7‰ and 1.7‰ with depth in SH and KH sites respectively, while YEK site had the maximum value and variation of $\delta^{15}N$‰. The $\delta^{13}C$ values for mangrove sediments range from −29.4‰ to −20.6‰ (Bouillon et al., 2003).

The TOC:TN molar ratios have been broadly employed to indicate organic matter sources and fate in mangrove forests (Prasad et al., 2017). The higher TOC:TN ratios (~11) and the lower $\delta^{13}C$and $\delta^{15}N$ values (−25, 4.4%) in KH indicates that this site contains a larger ratio of organic matter input derived from in situ mangrove debris than the other sites, indicating a greater marine source to this study area. The higher sediment OC stocks in KH estuary may be caused by higher amounts of root derived-carbon where the preference anaerobic conditions has reduced mineralization. Historical bathymetry data delineated that the mouth of KH estuary had significant marine particle sedimentation (Etemadi, 2014) that cause less marine particulate organic matter imported to the KH mangroves. The upper estuarine region of the Red River and Thuy National Park Mangroves of Vietnam with similar $\delta^{13}C$ and TOC:TN ranges of our study ($\delta^{13}C$ −24.6 and −24.81‰, TOC:TN ratios (~11) and (~8) in sediment respectively) was determined to be mainly composed of mangrove sources (Tue et al., 2011, 2012). Also, terrestrial and mangrove organic matter contributed to the significant amounts of sedimentary OC in upstream Indian Sundarban mangroves (with $\delta^{13}C$ −21.5 to −26.6‰, C:N ratios 10–11) (Prasad et al., 2017).

The elevated $\delta^{15}N$ levels at the YEK site indicates that the accumulation of ^{15}N compounds are derived from anthropogenic nitrogen sources. The YEK mangrove forests are located near Jask city, which would explain the higher $\delta^{15}N$ as this area may receive more anthropogenic nitrogen from the city. Significantly lower organic carbon (0.3%) concentration, and the higher $\delta^{13}C$ (−21%),TOC:TN ratios (9.7) and $\delta^{15}N$ (9.1%) values were found in YEK mangrove zone, that indicated allochthonous sources, such as algae and marine particulate organic matter was most likely the dominant source of carbon in this mangroves. Because, seawater flows through a long spiral channel to reach YEK mangroves, this shallow water with likely anthropogenic nitrogen content makes this area susceptible to algae growth. According to Kristensen et al. (2008) relatively enriched $\delta^{13}C$data (−17 to −23%) demonstrates large inputs of imported phytoplankton, seagrasses and micro-phytobenthos carbon sources. Furthermore, algae and marine material may be a significant sources of organic matter to the SH estuary, due the neighboring fishing docks which export nitrogen and phosphors to the coast. The presence of bacteria can introduce N to the sediment and thus decrease C:N ratios. Bacteria and algae typically have low C:N ratios of 4–6 and < 10, respectively. Furthermore marine algae have a variable range of $\delta^{13}C$ between −16% and −23% with an average $\delta^{13}C$ value for marine phytoplankton near-22‰ compared to −17‰ for marine benthic algae (Meyers, 1994). Low C:N ratios coincide with lower OC stock and less negative $\delta^{13}C$ values indicate a marine and planktonic origin to the mangrove sedimentary carbon pool such as the mangroves systems in Coringa Indian (Bouillon et al., 2003). Allochthones marine input can also represent a significant fraction of the sedimentary organic carbon such as in mangrove-fringed coast in French Guiana (C:N, 6–8) and fringe zone of New Zealand (Pollen Island) mangroves (C:N (13.1) and $\delta^{13}C$ values (−23.3‰)) (Marchand et al., 2003; Yang et al., 2013).

The Jegin and Gabrik Rivers located in the Gabrik protected area are considered seasonal rivers which do not have a constant flow throughout the year. Therefore, there is a possibility of river-

transported terrestrial material to GET estuary that cause a more negative $\delta^{13}C$ and higher $\delta^{15}N$ compared to the SH and KH sites. Phytoplanktonic and benthic microalgae carbon sources represent the heavier values of $\delta^{13}C$ (> -24‰) in mangrove sediment while the lightest $\delta^{13}C$ value (near −26.5‰) suggest terrestrial vegetation endmember (Pérez et al., 2017). Therefore, a mixture of marine POC and microalgae with terrestrial inputs likely contribute organic carbon sources in the GET mangrove estuary. Although, marine inputs represent significant fraction of this mangrove carbon sources.

The $\delta^{13}C$and $\delta^{15}N$ values in this work are within ranges of Indian (−26.8 to −10.9, 0.09–12.44) and in Bangladesh (−23.54 to −13.14, 0.05–17.55) mangroves ecosystems, respectively (Prasad et al., 2017). In general, marine organic material is characterized by low OC (0.5–3%), low TOC:TN ratios (6−12), and variable $\delta^{13}C$ (−28 to −16‰) (Prasad et al., 2017). The range of OC%, TOC:TN ratio and $\delta^{13}C$ of the results in this work are comparable to Lamb et al. (2006), which reinforces the assertion that the marine POC and microalgae inputs are dominant inputs at all the study sites, with the exception on KH. Ray and Shahraki (2016) similarly suggested that the growth of benthic microalgae at the Qeshm mangroves in Iran controls the organic carbon and nitrogen dynamics in the sediment. Based on these results and the fact that algal-derived OC is much more labile than higher plant-derived organic matter (Marchand et al., 2003), we suggested that this is one of the causes in the low carbon content found in these Iranian mangrove sediments.

Environmental variables such as drought, salinity stress temperature fractionation and nutrient limitation may cause stunted mangroves which can affect C3 plant photosynthesis, showing distinctly more enriched $\delta^{13}C$ values (Seemann and Critchley, 1985). Given the results presented here, it is apparent that the Iranian mangroves are experiencing physiological stress including from salinity (> 39), humidity and temperature (> 35 °C in summer) that may be causing higher $\delta^{13}C$ (−23.5%) compared to other mangrove forest. Wooller et al. (2003) indicated that slightly higher $\delta^{13}C$ values in the *Laguncularia racemosa* forests may be due to higher salinity in some parts of the Florida as compared to Belize. Also, for the Kenya mangroves, $\delta^{13}C$ POC in the freshwater zone was around −28 to −27‰, and increased up to −16‰ in salinities of near of 36‰, (Bouillon et al., 2008).

6. Conclusions

Landward mangrove migration and expansion was found to be substantial in East Jask and Gabrik mangroves, as the result of the well-documented sea level rise (2.8 mm yr^{-1}) in this region. Furthermore, the data in this study shows that of the sequestration OC in the arid mangrove soils of this region are partially offset by CO_2 production associated with inorganic carbon calcification processes. Our investigations show that the KH site, located in the East Jask protected area, contained a greater organic matter input derived from autochthonous mangrove source as a result of the significant marine particle sedimentation at the mouth of KH estuary. The results also indicated that greater allochthonous sources, such as algae and marine particulate organic matter, were deposited at the YEK site (near Jask city) and SH (near fishing dock). River-transported terrestrial material to GET estuaries (influence by seasonal rivers) were found to be related to the more negative $\delta^{13}C$ and higher $\delta^{15}N$ values compared to SH and KH sites without any river input. Further studies in arid mangroves are needed as the current global carbon stock estimates do not take into account the effect of mangrove migration and carbonate offset of these systems.

References

Almahasheer, H., Al-Taisan, W., Mohamed, M.K., 2013. Mangrove deterioration in Tarut Bay on the eastern province of the Kingdom of Saudi Arabia. Pakhtunkhwa J. Life Sci. 01, 49–59.

Almahasheer, H., Duarte, C.M., 2015. Decadal stability of red sea mangroves. Estuar. Coast Shelf Sci. 169, 164–172. https://doi.org/10.1016/j.ecss.2015.11.027.

Alothman, A., Bos, M., Fernandes, R., Ayhan, M., 2014. Sea level rise in the northwestern part of the Arabian Gulf. J. Geodyn. 81, 105–110.

Abel, N.A.N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., Heyenga, S., 2011. Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. Environ. Sci. Pol. 14, 279–288.

Alongi, D.M., 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar. Coast Shelf Sci. 76, 1–13.

Alongi, D.M., 2015. The impact of climate change on mangrove forests. Curr Clim Change Rep 1 (1), 30–39. https://doi.org/10.1007/s40641-015-0002-x.

Azizpour, J., Chegini, V., Khosravi, M., Einali, A., 2014. Study of the physical oceanographic properties of the Persian Gulf, strait of Hormuz and Gulf of Oman based on PG-GOOS CTD measurements. J. Persian Gulf 5, 37–48.

Borges, A.V., Delille, B., Frankignoulle, M., 2005. Budgeting sinks and sources of CO_2 in the coastal ocean: diversity of ecosystems counts. Geophys. Res. Lett. 32http://dx.doi.org/10.1029/2005GL023053. L14601.

Bouillon, S., Dahdouh-Guebas, F., Rao, A.V.V.S., Koedam, N., Dehairs, F., 2003. Sources of organic carbon in mangrove sediments: variability and possible ecological implications. Hydrobiologia 495, 33–39.

Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, V.H., Smith, T.J., Twilley, R.R., 2008. Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochem. Cycles 22, 1–12. https://doi.org/10.1029/2007GB003052.

Breithaupt, J.L., Smoak, J.M., Smith, T.J., Sanders, C.J., Hoare, A., 2012. Mangrove organic carbon burial rates: strengthening the global budget. Global Biogeochem. Cycles 26 GB3011.

Chen, G., Chen, B., Yu, D., Tam, N.F.Y., Ye, Y., Chen, S., 2016. Soil greenhouse gas emissions reduce the contribution of mangrove plants to the atmospheric cooling effect Soil greenhouse gas emissions reduce the contribution of mangrove plants to the atmospheric cooling effect. Environ. Res. Lett. 11 124019. https://doi.org/http://dx.doi.org/10.1088/1748-9326/11/12/124019.

Chimner, R.A., Fry, B., Kaneshiro, M.Y., Cormier, N., 2006. Current extent and historical expansion of introduced mangroves on Oahu. Hawaii. Pac Sci. 60, 377–383.

Danekar, A., 1996. Iranian mangrove forests. The Environ Sci Quart 8 (8), 22–32.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. https://doi.org/10.1038/NGEO1123.

Etemadi, H., 2014. Assessment and Predicting Climate Change Influence on Iran Mangrove Forests: a Case Study within the Jask Mangrove Protected Area. PhD Thesis, Dissertation. Department of Environment, Faculty of Natural Resources, Tarbiat Modarres University, Tehran.

Etemadi, H., Samadi, S., Sharifikia, M., Smoak, J.M., 2015. Assessment of climate change downscaling and non-stationarity on the spatial pattern of a mangrove ecosystem in an arid coastal region of southern Iran. Theor. Appl. Climatol. https://doi.org/10.1007/s00704-015-1552-5.

Etemadi, H., Smoak, J.M., Karami, J., 2018. Land use change assessment in coastal mangrove forests of Iran utilizing satellite imagery and CA–Markov algorithms to monitor and predict future change. Environ Earth Sci. https://doi.org/10.1007/s12665-018-7392-8.

Ezcurra, P., Ezcurra, E., Garcillán, P.P., Costa, M., Aburto-Oropeza, O.T., 2016. Coastal landforms and accumulation of mangrove peat increase carbon sequestration and storage. Proc. Natl. Acad. Sci. Unit. States Am. 113, 4404–4409.

Frankignoulle, M., Pichon, M., Gatusso, J.P., 1995. Aquatic calcification as a source of carbon dioxide. Universite de liege 133, 265–271.

Gacia, E., Duarte, C.M., Middelburg, J.J., 2002. Carbon and nutrient deposition in a Mediterranean seagrass (Posidoniaoceanica) meadow. Limnol. Oceanogr. 47, 23–32. https://doi.org/10.4319/lo.2002.47.1.0023.

Hak, J., Medellin, X.L., Beltran, J.M., Josse, C., Stein, B., White, R., 2008. Mapping and analysis of mangrove habitat extent change in Baja California sur from 1986 to 2001. Natureserve, Arlington, USA. Available at: http://research.fit.edu/sea level rise library/documents/doc_mgr/472/Baja_ alifornia_Sur_Mangrove_ Changes_1986-2001_-_Hak_ et_al._2008.pdf.

Howard, J.L., Creed, J.C., Aguiar, M.V.P., Fouqurean, J.W., 2017. CO_2 released by carbonate sediment production in some coastal areas may offset the benefits of seagrass "BlueCarbon" storage. Limnol. Oceanogr. https://doi.org/10.1002/lno.10621.

IPCC, 2013. Climate Change 2013. The Physical Science Basis. Summary for Policymakers. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jafari, M., Tavili, A., Panahi, F., Zandi Esfahan, E., Ghorbani, M., 2018. Characteristics of arid and desert ecosystems. Environmental science and engineering (subseries: environmental science). https://doi.org/10.1007/978-3-319-54828-9_2.

Kairo, J.G., 2001. Ecology and Restoration of Mangrove Systems in Kenya. PhD thesis, APNA. Vrije Universiteit Brussels, Belgium.

Krauss, K.W., From, A.S., Doyle, T.W., Doyle, T.J., Barry, M.J., 2011. Sea-level rise and landscape change influence mangrove encroachment onto marsh in the Ten Thousand Islands region of Florida, USA. J. Coast Conserv. 15, 629–638.

Kristensen, E., Bouillon, S., Dittmar, T., Marchand, C., 2008. Organic carbon dynamicsin mangrove ecosystems: a review. Aquat. Bot. 89, 201–219.

Lamb, A.L., Wilson, G.P., Leng, M.J., Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeo-climate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. Earth Sci. Rev. 75, 29–57. https://doi.org/10.1016/j.earscirev.2005.10.003.

López-Medellín, X., Ezcurra, E., González-Abraham, C., Hak, J., Santiago, L.S., Sickman, J.O., 2011. Oceanographic anomalies and sea-level rise drive mangroves inland in the

Pacific coast of Mexico. J. Veg. Sci. 22 (1), 143–151.
Marchand, C., Lallier-Vergès, E., Baltzer, F., 2003. The composition of sedimentary organic matter in relation to the dynamic features of a mangrove-fringed coast in French Guiana Estuary. Coast. Shelf Sci. 56, 119–130.
Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chem. Geol. 114, 289–302.
McConnaughey, T., Labaugh, J.W., Rosenberry, D.O., Striegl, R.G., Reddy, M.M., Schuster, P.F., Carter, V., 1994. Carbon budget for groundwater fed lake: calcification supports summertime photosynthesis. Limnol. Oceanogr. 39 (6), 1319–1332.
McLeod, E., Salm, R.V., 2006. Managing mangroves for resilience to climate change. IUCN, Gland, Switzerland, pp. 74.
Pérez, A., Machado, W., Gutierrez, D., Stokes, D., Sanders, L., Smoak, J.M., Santos, I., Sanders, C.J., 2017. Changes in soil organic carbon accumulation driven by mangrove expansion and deforestation in a New Zealand estuary. Estuar. Coast Shelf Sci. https://doi.org/10.1016/j.ecss.2017.05.009.
Perry, C.L., Mendelssohn, I.A., 2009. Ecosystem effects of expanding populations of *Avicenniagerminans* in a Louisiana salt marsh. Wetlands 29 (1), 396–406.
Prasad, M.B.K., Ramanathan, A.L., 2009. Organic matter characterization in a tropical estuarine-mangrove ecosystem of India: preliminary assessment by using stable isotopes and lignin phenols. Estuar. Coast Shelf Sci. 84 (4), 617–624.
Prasad, M.B.K., Kumar, A., Ramanathan, A.L., Kumar Datta, D., 2017. Sources and dynamics of sedimentary organic matter in Sundarban mangrove estuary from Indo-Gangetic delta Sources and dynamics of sedimentary organic matter in Sundarban mangrove estuary from Indo-Gangetic delta, (April). https://doi.org/10.1186/s13717-017-0076-6.
Ramcharan, E.K., 2004. Mid-to-late Holocene sea level influence on coastal wetland development in Trinidad. Quat. Int. 120, 145–151.
Ray, R., Rixen, T., Baum, A., Malik, A., Gleixner, G., Jana, T.K., 2015. Distribution, sources andbiogeochemistry of organic matter in a mangrove dominated estuarine system (*IndianSundarbans*) during the pre-monsoon. Estuar. Coast Shelf Sci. https://doi.org/10.1016/j.ecss.2015.10.017.
Ray, R., Shahraki, M., 2016. Science of the Total Environment Multiple sources driving the organic matter dynamics in two contrasting tropical mangroves. Sci Environ 571, 218–227. https://doi.org/10.1016/j.scitotenv.2016.07.157.
Saderne, V., Cusack, M., Almahasheer, H., Serrano, O., Arias-ortiz, A., Krishnakumar, P.K., 2018. Accumulation of carbonates contributes to coastal vegetated ecosystems keeping pace with sea level rise in an arid region (Arabian Peninsula). Am. Geophys. Union 2050, 1–13. https://doi.org/10.1029/2017JG004288.
Sánchez-Andrés, R., Sánchez-Carrillo, S., Alatorre, L.C., Cirujano, S., Álvarez-Cobelas, M., 2010. Litter-fall dynamics and nutrient decomposition of arid mangroves in the Gulf of California: their role sustaining ecosystem heterotrophy. Estuar. Coast Shelf Sci. 89 (3), 191–199. https://doi.org/10.1016/j.ecss.2010.07.005.
Sanders, C.J., Eyre, B.D., Santos, I.R., Machado, W., Luiz-Silva, W., Smoak, J.M., Breithaupt, J.L., Ketterer, M.E., Sanders, L., Marotta, H., Silva-Filho, E., 2014. Elevated rates of organic carbon, nitrogen,and phosphorus accumulation in a highly impacted mangrove wetland. Geophys. Res. Lett. 41, 2475–2480.
Sanders, C.J., Maher, D.T., Tait, D.R., Williams, D., Holloway, C., Sippo, J.Z., Santos, I.R., 2016. Are global mangrove carbon stocks driven by rainfall? J. Geophys. Res. Biogeosci 121, 2600–2609 c10.1002/2016JG003510.
Schile, L.M., Kauffman, J.B., Crooks, S., Fourqurean, J.W., Glavan, J., Megonigal, J.P., 2016. Limits on carbon sequestration in arid blue carbon ecosystems. Ecol. Appl. https://doi.org/10.1002/eap.1489.
Sea, M.A., Garcias-bonet, N., Saderne, V., Duarte, C.M., Sea, R., 2018. Carbon dioxide and methane emissions from red sea mangrove sediments. Biogeosciences 1–24.
Seemann, J.R., Critchley, C., 1985. Effects of salt stress on the growth, ion content, stomatal behaviour and photosynthetic capacity of a salt-sensitive species. Phaseolus vulgaris L. Planta 164, 151–162.
Smoak, J.M., Breithaupt, J.L., Smith, T.J., Sanders, C.J., 2013. Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park. Catena 104, 58–66. https://doi.org/10.1016/j.
Solaimani Rad, A., 2011. The Study of Macrobenthos Community Structure in Jask Mangrove Protected Area. Dissertation submitted to Department of Environment. Faculty of Science, Hormozgan University, Bandar-Abbas.
The State of Food and Agriculture (FAO), 2007. ISBN 978–92–5-105,750–6.
Tue, N.T.T., Amaoka, H.H., Ogabe, A.S., Uy, T.D.Q., 2011. Sources of sedimentary organic carbon in mangrove ecosystems from Ba Lat estuary, Red River, Vietnam. Interdisciplinary Studies on Environmental Chemistry—Marine Environmental Modeling & Analysis 151–157.
Tue, N.T., Ngoc, N.T., Quy, T.D., Hamaoka, H., Nhuan, M.T., Omori, K., 2012. A cross-system analysis of sedimentary organic carbon in the mangrove ecosystems of Xuan Thuy National Park. Vietnam. J. Sea Res 67 (1), 69–76. https://doi.org/10.1016/j.seares.2011.10.006.
Woodworth, P., Foden, P., Pugh, J., Mathews, A., Aarup, T., Aman, A., Nkebi, e., Odametey, J., Facey, R., Esmail, M.Y.A., Ashraf, M., 2009. Insight into long term sea level change based on new tide gauge installations at Takoradi, Aden and Karachi. IHR 1, 18–23.
Wooller, M., Smallwood, B., Jacobson, M., Fogel, M., 2003. Carbon and nitrogen stable isotopic variation in Laguncularia racemosa (L.) (Whitemangrove) from Florida and Belize: implications for trophic level studies. Hydrobiologia 499, 13–23.
Yang, J., Gao, J., Cheung, A., Liu, B., Schwendenmann, L., Costello, M.J., 2013. Vegetation and sediment characteristics in an expanding mangrove forest in New Zealand. Estuar. Coast. Shelf Sci. 134, 11–18. https://doi.org/10.1016/j.ecss.2013.09.017.